Global Anisotropies in Supernova Explosions and Pulsar Recoil

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Observations show that neutron stars can have space velocities much higher than those of their progenitors. On average pulsar birth velocities are in the range of 200-500 km/s and significant fraction might move with more than 1000 km/s (see [1] and references therein). The powerful and highly variable acceleration mechanism that leads to the measured velocities is still unclear. It is possible that a recoil velocity is imparted to the neutron star by explosion asymmetries at the moment of its birth. Herant [3] suggested that an $l = 1$ mode might cause an asymmetry that is sufficiently large to explain pulsar velocities even in excess of 1000 km/s.

However, in previous simulations only anisotropies on relatively small angular scales have been found. Consequently, the neutron star kicks did not exceed 100-200 km/s (see e.g. [5]). Motivated by the hypothesis that the rapid onset of the explosion in these models did not allow the merging of small-scale anisotropies to global modes, we started to conduct a new study of about 50 two-dimensional simulations, where the explosion, based on the neutrino-heating mechanism, was triggered such that the initial expansion set in more slowly [6].

The neutron star core in these simulations was replaced by a boundary condition. In contrast to earlier simulations, we prescribed more *slowly* decaying and initially lower neutrino luminosities at this boundary. This leads to longer explosion time scales and thus gives convective structures between neutron star and shock more time to merge. Shortly after the onset of the explosion most of our models are dominated by an $l = 1$ mode of the mass distribution: Infalling stellar material is concentrated in one downflow and neutrino-heated matter rises in one bubble on the opposite side. We found highly anisotropic explosions for three different 15 solar mass progenitors. A rotating progenitor (from [2]) also developed low-mode structures.

Figure 1 displays neutron star velocities and accelerations one second after core bounce. We found neutron star velocities as high as 520 km/s with still large acceleration after the first second. The final neutron star velocities can therefore be significantly higher. The dominant force that mediates the acceleration is the gravitational attraction by the anisotropic ejecta. Therefore the neutron star moves towards the most slowly expanding ejecta, opposite to the main direction of the explosion. Most of the acceleration takes place after the onset of the explosion, substantial acceleration may continue for several seconds.

It has to be shown that the merging of modes in three dimensions is as efficient as in two. A first 3D simulation with still relatively low resolution also developed an $l = 1$ mode and is therefore promising (see figure 2). Simulations with higher resolution are in progress [7].

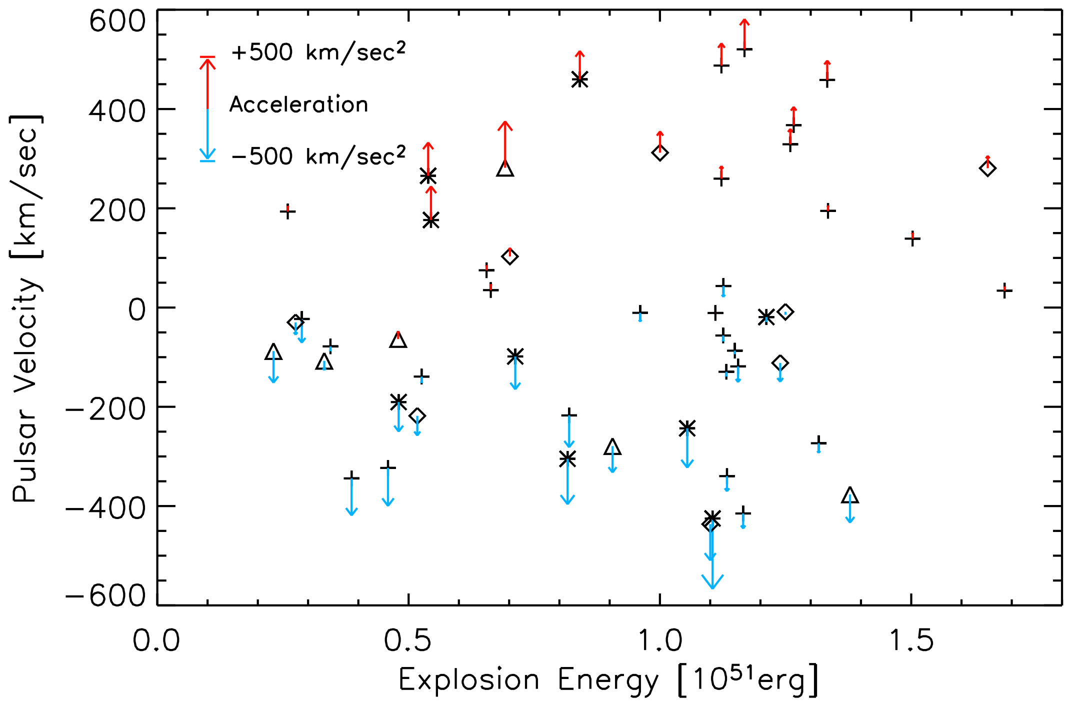

Figure 1: Neutron star velocities and accelerations at one second after core bounce for a sample of simulations [4]. Different symbols denote different progenitor stars.

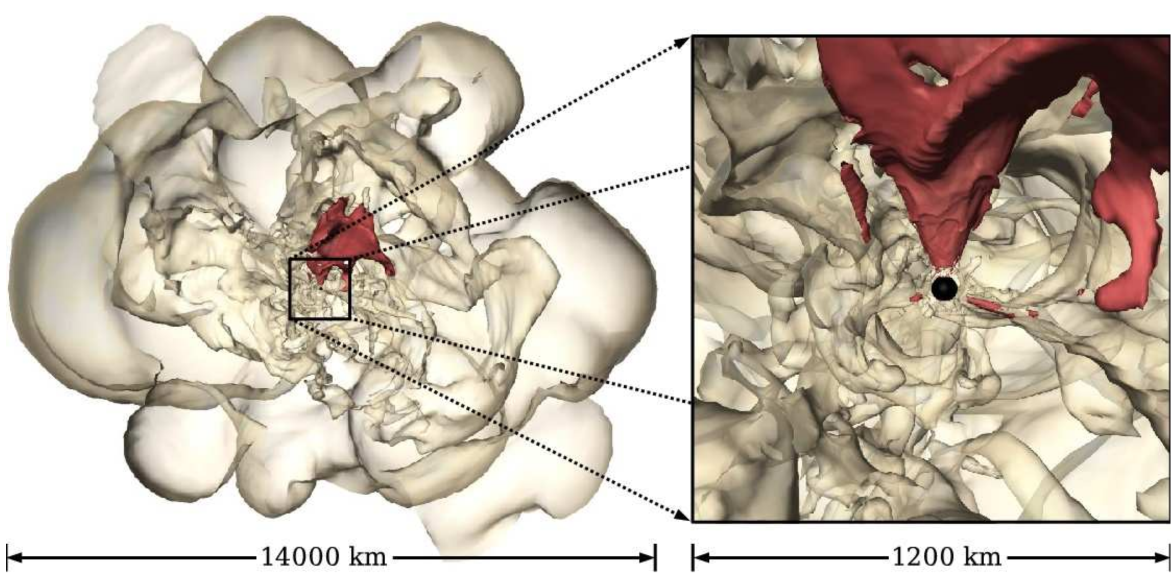

Figure 2: Three-dimensional simulation [7] one second after core bounce. The bright structure is a surface of constant proton-to-neutron ratio which roughly marks the outer boundaries of the neutrino-heated high-entropy bubbles. The dark surface, blown up in the right figure, is defined by a constant value for the mass flux per unit area and defines a downflow of matter towards the neutron star, the surface of which is indicated by the black sphere (corresponding to a density of 10^{11}g/cm^3).

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